

Probing cosmological isotropy with Planck Sunyaev-Zeldovich galaxy clusters

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25 July 2016

ABSTRACT

We probe the assumption of statistical isotropy with the second Planck Sunyaev-Zeldovich (PSZ2) galaxy clusters data set. Our analyses are performed with a statistical-geometrical method, in which the 2-point angular correlation function of such objects in antipodal patches of the sky is computed. Accordingly, possible observational bias, such as foreground mask and anisotropic sky exposure, are taken into account in ensembles of Monte Carlo realisations produced in order to assess the significance of our results. We report no significant evidence for a preferred direction, or any remarkable large-angle features in our analyses. Therefore, the sky distribution of PSZ2 objects presents good agreement with the hypothesis of statistical isotropy.

Key words: Cosmology; Observations; large-scale structure of Universe; galaxy clusters

1 INTRODUCTION

The Cosmological Principle (CP) consists on a fundamental assumption in modern cosmology in which the Universe presents neither special directions, nor special positions, is a , (see, e.g. [Goodman \(1995\)](#); [Maartens \(2011\)](#) for discussions about this subject). In this sense, the success of FLRW-based models, such as the Λ CDM scenario, in explaining the angular power spectrum of the Cosmic Microwave Background (CMB) temperature fluctuations ([Ade et al. 2015a](#)), the evolution of large-scale structure of the Universe (LSS) ([Aubourg et al. 2015](#)), as well as the cosmological distances and ages ([Alcaniz & Lima 1999](#); [Alcaniz et al. 2003](#); [Simon et al. 2005](#); [Stern et al. 2010](#); [Moresco et al. 2012](#); [Suzuki et al. 2012](#); [Betoule et al. 2014](#)), has solidified the CP not as a simplified mathematical hypothesis but as a valid physical assumption. Therefore, it is of great importance to test the CP with observational data not only for the sake of probing one of the underpinning assumptions of cosmology, but also for correctly interpreting the mechanism behind cosmic acceleration and structure formation.

However, there are claims of possible statistical isotropy violation in large scales, where many of them are ascribed to the features in CMB temperature fluctuations data such as low multipole alignments, hemispherical power asymmetries, lack of angular correlations at large scales, and the presence of a non-gaussian Cold Spot ([Eriksen et al. 2004](#); [Bernui et al. 2007](#); [Abramo et al.](#)

[2009](#); [Akrami et al. 2014](#); [Bernui et al. 2014](#); [Ade et al. 2015d](#); [Schwarz et al. 2015a](#)). Moreover, the presence of very large velocity flows when compared reference value of velocity of our relative motion toward the CMB obtained by [Kogut et al. \(1993\)](#); [Aghanim et al. \(2014\)](#), that is, $v \approx 370$ km/s, were suggested (to some controversy) by kinematic Sunyaev-Zeldovich effect analyses using galaxy clusters ([Kashlinsky et al. 2009, 2011](#); [Atrio-Barandela et al. 2015](#)), or by anomalously large number count dipoles found in high- z radio sources maps ([Blake & Wall 2002](#); [Singal 2011](#); [Rubart & Schwarz 2013](#); [Fernández-Cobos et al. 2014](#); [Tiwari et al. 2015](#); [Tiwari & Nusser 2016](#)), thus posing potential challenges for the isotropy assumption as well. The possibility of anisotropy in the cosmological expansion were also investigated with Type Ia Supernovae luminosity distance ([Schwarz & Weinhorst 2007](#); [Antoniou & Perivolaropoulos 2010](#); [Cai & Tuo 2012](#); [Turnbull et al. 2012](#); [Kalus et al. 2013](#); [Feindt et al. 2013](#); [Jiménez et al. 2015](#); [Appleby et al. 2015](#); [Bengaly et al. 2015](#); [Javanmardi et al. 2015](#)), yet no significant result supporting this possibility has been detected so far.

In the light of these puzzles, the validity of the CP must be put under scrutiny with the latest observational data, since any other detected violation of its underlying hypotheses would reinforce the demand of a complete reformulation of the standard cosmological scenario. A direct method to test isotropy consists on searching for a dipole asymmetry, or directional anomalous features in the angular distribution of cosmic objects, once they are projected on the celestial sphere. The second release of Planck Sunyaev-Zeldovich (PSZ2) catalogue ([Ade et al. 2015b,c](#)) provides an ideal sample for this purpose since it comprises over 1600 galaxy clusters (GCs) in a wide sky coverage ($f_{\text{sky}} \approx 0.83$), besides a deep redshift

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range ($z \leq 0.8$), hence the most complete all-sky GCs set by the current moment. As these objects are good representatives of the matter distribution of the Universe, they should not exhibit directional dependence of their projected distribution in the sky. So, any anomalous signal of this nature, such as regions presenting excess of correlations (clustering) or anti-correlations (voids) in the GCs angular distribution, are suggestive of violation of the cosmological isotropy assumption (and hence a violation of the CP), unless explained by limited sky coverage, and systematics, of the observational sample.

Therefore, we analyse the statistical isotropy of the PSZ2 sources by carrying out a hemispherical comparison, based on the 2-point angular correlation function, through the celestial sphere. The statistical significance of this analysis is estimated with synthetic Monte Carlo realisations that account for the cut-sky GCs maps around the galactic plane, besides the sky exposure of Planck's observational strategy, as they could explain the existence of over-dense and under-dense source distribution in some patches of the sky. The paper is organised as follows: section 2 is dedicated to the preparation of the data set we adopt throughout this work, section 3 discusses the methodology developed to carry out the statistical isotropy analysis of the GCs angular distribution, and finally our results and final remarks are presented in section 4 and 5, respectively.

2 DATA SET PREPARATION

Our analyses are performed with the PSZ2 catalogue named Union (henceforth *PSZ2-Union*), which has been downloaded from the IRSA website¹. This set encompasses GCs compiled from three combined detection methods based on neural network algorithms. The main systematics of this data set consists on spurious infra-red contamination, besides the limitation of neural algorithm failure in the GCs detection. Hence, we apply the following queries on the PSZ2-Union original catalogue:

- $\text{IR}_{\text{FLAG}} < 1$,
- $\text{Q}_{\text{NEURAL}} > 0.4$,
- $z > -1$.

The first two queries eliminate 180 of 1654 objects, already providing a sample purity of 85%, whereas the last one reduces the sample to 1066 GCs. While redshift is not the main source of uncertainty, we note that the exclusion of the GCs with no redshift determination contributes to increase the overall signal-to-noise (S/N) of their detection, hence comprising the most reliable sources of the catalogue². The final sample we use throughout this paper is exhibited as black dots in the left panel of Figure 1, and whose corresponding foreground mask appears in the right panel. As previously mentioned, the available celestial area for our analysis, in order to avoid spurious contamination due to dust thermal emission, is $f_{\text{sky}} \simeq 0.83$

¹ <http://irsa.ipac.caltech.edu>

² Note also that there is a sub-set of the PSZ2 catalogue, named PSZ2-COSMOLOGY, consisting of the highest-quality GCs ($S/N \geq 6$) in $f_{\text{sky}} \simeq 0.65$), that has been constructed by the Planck team to constrain cosmological parameters such as Ω_m and σ_8 (Ade et al. 2015c). We do not focus on this sample as our goal is to test the isotropy assumption with the largest set possible in terms of data points, besides sky coverage, yet it gives similar results to the larger PSZ2-Union set.

3 METHODOLOGY

3.1 The Sigma-Map

Here we describe the angular-distribution estimator which leads to quantify deviations from statistical isotropy in a given set of cosmic events with known positions on the celestial sphere (Bernui et al. 2007, 2008). Our primary purpose is to illustrate the procedure for defining the discrete function σ on the celestial sphere in order to generate its associated map, called σ -map or sigma-map. Then, one compares the sigma-map obtained from the data catalogue with a large set of sigma-maps generated from statistically isotropic simulated ensembles in order to assess a measure of (possible) deviation from statistical isotropy in the dataset in analysis.

Let $\Omega_j^{\gamma_0} \equiv \Omega(\theta_j, \phi_j; \gamma_0) \in \mathcal{S}^2$ be a spherical cap region on the celestial sphere, of γ_0 degrees of radius, centered at the j -th pixel, $j = 1, \dots, N_{\text{caps}}$, where (θ_j, ϕ_j) are the angular coordinates of the center of the j -th pixel. Both, the number of spherical caps N_{caps} and the coordinates of their center (θ_j, ϕ_j) are defined using the HEALPix pixelization scheme (Górski et al. 2005). The spherical caps are such that their union completely covers the celestial sphere \mathcal{S}^2 . We assume galactic coordinates throughout our analyses. Let C^j be the catalogue of cosmic objects located in the j -th spherical cap $\Omega_j^{\gamma_0}$. The 2-point angular correlation function (2PACF) of these objects (Padmanabhan 1993), denoted as $\Delta_j(\gamma_i; \gamma_0)$, is the difference between the normalised frequency distribution and that expected from the number of pairs-of-objects with angular distances in the interval $(\gamma_i - 0.5\delta, \gamma_i + 0.5\delta]$, $i = 1, \dots, N_{\text{bins}}$, where $\gamma_i \equiv (i - 0.5)\delta$ and $\delta \equiv 2\gamma_0/N_{\text{bins}}$ is the bin width. The expected distribution is the average of normalized frequency distributions obtained from a large number of simulated realisations of isotropically distributed objects in \mathcal{S}^2 , containing the same number of objects as in the dataset in analysis. This 2PACF estimator is nothing else than the well known $DD - RR$, termed *natural* estimator in the literature (Bernui & Teixeira 1999; Bernui 2005). A positive (negative) value of Δ_j indicates that objects with these angular separations are correlated (anti-correlated), while zero indicates no correlation.

Let us define now the scalar function $\sigma : \Omega_j^{\gamma_0} \mapsto \mathcal{R}^+$, for $j = 1, \dots, N_{\text{caps}}$, which assigns to the j -cap, centered at (θ_j, ϕ_j) , a real positive number $\sigma_j \equiv \sigma(\theta_j, \phi_j) \in \mathcal{R}^+$. We define a measure σ of the angular correlations in the j -cap as

$$\sigma_j^2 \equiv \frac{1}{N_{\text{bins}}} \sum_{i=1}^{N_{\text{bins}}} \Delta_j^2(\gamma_i; \gamma_0). \quad (1)$$

To obtain a quantitative measure of the angular correlation signatures of the GC's sky map, we choose $\gamma_0 = 90^\circ$ and cover the celestial sphere with $N_{\text{caps}} = N_{\text{hemis}} = 768$ hemispheres, then calculate the set of values $\{\sigma_j, j = 1, \dots, N_{\text{caps}}\}$ using eq. (1). Patching together the set $\{\sigma_j\}$ in the celestial sphere according to a coloured scale (where, for instance, $\sigma^{\text{minimal}} \rightarrow \text{blue}$, $\sigma^{\text{maximal}} \rightarrow \text{red}$) we obtain a sigma-map. We quantify the angular correlation signatures of a given sigma-map from a data set by calculating its angular power spectrum. Similar power spectra are calculated, for comparison, with isotropically distributed samples of cosmic objects.

Since the sigma-map assigns a real number value to each pixel in the celestial sphere, that is, $\sigma = \sigma(\theta, \phi)$, it is possible expand it in spherical harmonics: $\sigma(\theta, \phi) = \sum_{\ell, m} A_{\ell m} Y_{\ell m}(\theta, \phi)$ where the set of values $\{S_\ell\}$, defined by $S_\ell \equiv (2\ell + 1)^{-1} \sum_{m=-\ell}^{+\ell} |A_{\ell m}|^2$, is the angular power spectrum of the sigma-map. Because we are interested in the

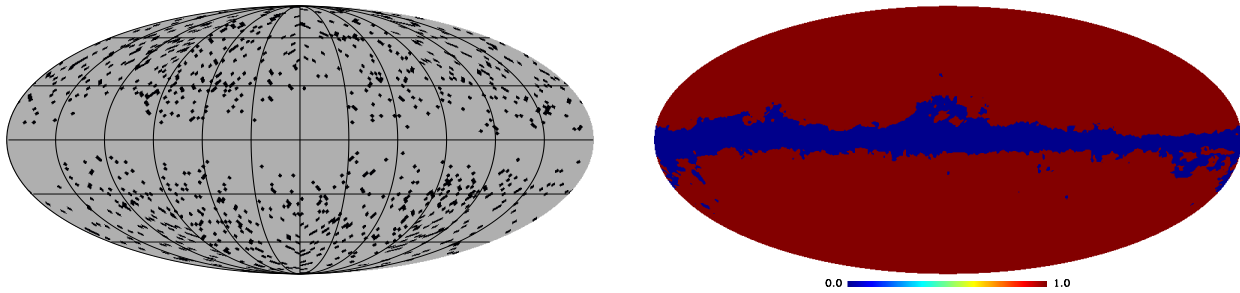


Figure 1. *Left panel:* The selected PSZ2 objects exhibited in Mollweide projection. *Right panel:* The foreground mask of the PSZ2-Union catalogue, whose available area (in red) is $f_{sky} \approx 0.83$

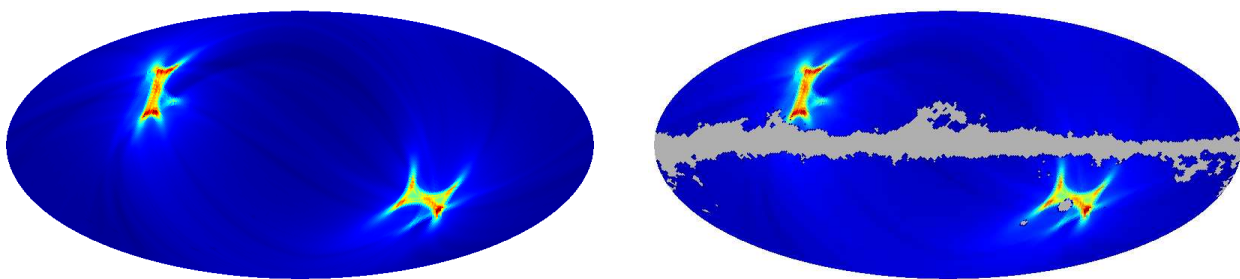


Figure 2. *Left panel:* The NUSE map of the Planck satellite, given in terms of the probability of observing a certain patch of the sky. *Right panel:* The same map after the proper mask is applied.

large-scale angular correlations, we shall concentrate on $\{S_\ell, \ell = 1, 2, \dots, 10\}$, i.e., scales larger than 18° in the sky.

3.2 Monte Carlo simulations

The statistical significance of our sigma-map analyses is evaluated with Monte Carlo (MCs) realisations. We shall compare the GCs angular distribution from the PSZ2 catalogue with a set of 500 purely isotropic data set with the same available area as the real data, termed *MCs iso*. The first step to produce this set of simulated data, the *MCs iso*, is to know how many points one has to generate in the whole celestial sphere. The number of GCs of the PSZ2 catalogue in the masked sky is $n_{GCs} = 1066$, which implies that the number of GCs to be observed in any full-sky simulation should be 17% larger because $f_{sky} \approx 0.83$. This results in that $n_{GCs} = 1284$ data points should be simulated in any full-sky MC realisation. The second step consists on generating, for each MC map, 1284 pairs of angular coordinates (θ, ϕ) , where $\theta \in [0, \pi]$, $\phi \in [0, 2\pi]$ ³. Let $R_n \in [-1, +1]$, $n = 1, \dots, 1284$, be a uniformly distributed random real number, then an ensemble of pairs of random numbers $\{(R_i, R_j)\}$ produce an ensemble of pairs of angular coordinates corresponding to isotropically distributed GCs: $(\theta_i, \phi_j) = (\text{ArcCos}(R_i), \pi(R_j + 1))$. For details of how to produce

maps with isotropically distributed points and how to test the statistical isotropy there see Bernui et al. (2004) (regarding the theoretical expected function of the estimator $DD-RR$ see, e.g., Bernui & Teixeira (1999); Bernui (2005)). The last step of this procedure is to apply the cut-sky mask to all of these simulated maps.

After that we have to produce a second set of MCs, that is, an ensemble of 500 MCs which takes the non-uniform sky exposure (NUSE) function of the Planck satellite, as featured in Figure 2, into account. This is performed by weighting the number of data points according to the right panel of this figure, as the experiment had visited some regions of the sky more often than others, so that there is a higher probability that a larger amount of GCs have been detected toward these bright celestial regions than the others, which could potentially bias our assessment of GCs isotropy due to this effect⁴. For instance, Bernui et al. (2008) showed that the NUSE function can explain small departures from isotropy observed in the BATSE short Gamma-Ray Bursts angular distribution, which disagrees with previous results that did not consider such effect, and found a remarkable anisotropy in such distribution. These synthetic realisations are henceforth referred as *MCs aniso*, so that we compare the PSZ2-Union sigma-map with both MC ensembles in

³ Equivalently $(\theta, \phi) \rightarrow (l, b)$, with $b \in [-\pi/2, \pi/2]$, $l \in [0, 2\pi]$, where $(0,0)$ is the galactic centre.

⁴ This NUSE map has been constructed using the average of the four lowest frequency channels NUSE of Planck's instrumentation, namely 100, 143, 217, and 353 GHz, since the exposure time for the two highest frequencies (i.e., 545 and 857 GHz) is quite different from the others in terms of the total number of observations of each pixel (N_{obs} , which could bias the final map).

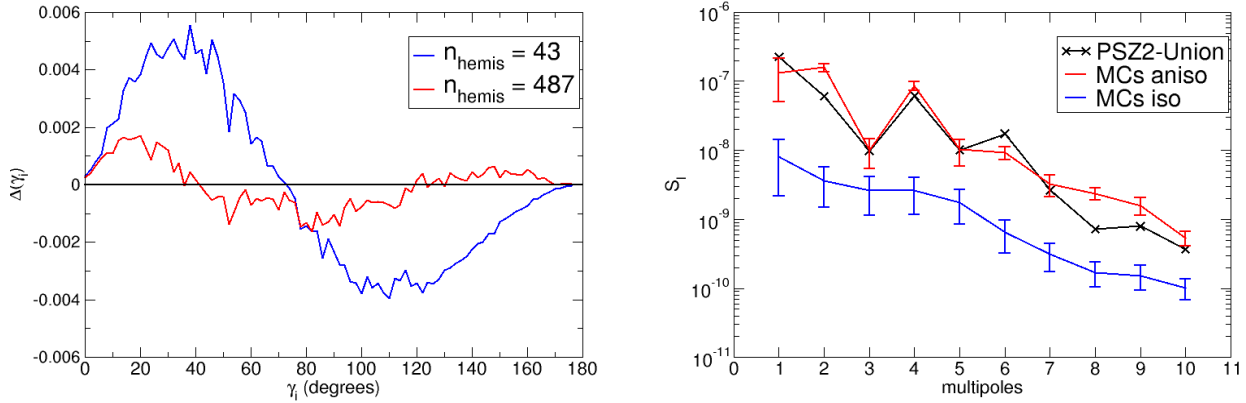


Figure 3. *Left panel:* We show the 2PACF $\Delta(\gamma_i)$ for two hemispheres obtained from the PSZ2-Union catalogue for illustrative reasons. $n_{\text{hemis}} = 43$ denotes the hemisphere position with maximal sigma-map, located at $(l, b) = (45.00^\circ, 60.43^\circ)$, while $n_{\text{hemis}} = 487$ stands for the hemisphere whose minimal sigma-map has been attained, centred towards $(l, b) = (247.50^\circ, -14.48^\circ)$. *Right panel:* The angular power spectrum S_ℓ of the PSZ2-union sigma-map result compared with the average power spectra obtained from the 500 isotropic (*MCs iso*, blue curve) and NUSE-based (*MCs aniso*, red curve) realisations.

order to estimate its directional variance given the limitations, i.e., the NUSE and foreground mask, that are intrinsic to the data, and could lead to a false anisotropic signal when unaccounted.

4 DATA ANALYSIS AND RESULTS

The left panel of Figure 3 depicts, for illustrative reasons, the 2PACF $\Delta(\gamma)$ (see Eq. (1)) obtained in two hemispheres along the angular distance γ from the hemisphere centre. The hemispheres $n_{\text{hemis}} = 43$ and $n_{\text{hemis}} = 487$, as indicated in this panel as the blue and red curves, respectively, correspond to those where the maximal and minimal sigma-map values (where the sigma-map denotes the sum of the square of this Δ over all these γ) have been attained, respectively. It is noticeable that the angular correlations fluctuates much more in the former case, hence indicating larger angular correlations (and anti-correlations) in the GCs distribution comprised in this region. When approximating the sigma-map results obtained through the whole celestial sphere as a dipole, we obtain a direction whose maximal value is located towards the north-western patch of the sky, and thereby the minimal points towards the south-east. Even though this direction resembles the maximal CMB power asymmetry localisation, we are unable to ascribe this signal to any of these features in a statistically significant manner. Thus, we report no signature of a preferred direction in the PSZ2-Union map that could be associated with the aforementioned CMB feature, as well as the dipole associated to the Hubble flow.

Moreover, the results of the sigma-map analyses in the form of the angular power spectrum, S_ℓ , are displayed as black crosses in the right panel of Figure 3. The red curve denotes the sigma-map results of 500 *MCs aniso* and, on the other hand, the blue curve represents the mean spectra obtained from idealistic isotropic maps that accounts only for the mask. In each case, the central values are given by their arithmetic average, while their spreads correspond the mean absolute deviation (MAD) of these simulated data sets. The use of MAD, instead of the standard deviation (STD), is due to the fact that the S_ℓ 's of these 500 MCs are very skewed to the right, i.e., they present a long-tailed distribution, therefore, the MAD gives a more robust estimation of their uncertainty around their

mean value than the STD. We note that the PSZ2-Union sigma-map behavior is much closer to the average of 500 *MCs aniso* than the purely isotropic realisations, yet the multipole moments S_2 , S_6 , and S_8 , corresponding to the angular scales 90° , 30° , and 22.5° , respectively, are slightly in tension with them. Such mild discrepancies could be ascribed to some unaccounted features in the data besides the anisotropic exposure function, and the incompleteness of the sky coverage, such as possible impurities and contamination that have not been detected in our quality tests, or even Planck team's. Nevertheless, we point out that these *MCs aniso* give the upper limit of the possible amount of anisotropy in each angular scale because of these selection effects, and since the apparent GCs distribution anisotropy matches this prediction in most of the angular scales probed, we conclude that no anisotropy other than those coming from selection effects has been revealed, and hence these data are in good agreement with the statistical isotropy hypothesis underlying the standard model of Cosmology.

5 CONCLUSIONS

The variety and robustness of current cosmological data provide the possibility of testing some fundamental hypotheses of the standard cosmological model. One of these hypotheses is the validity of the assumption of homogeneity and isotropy on very large scales. In this work, the cosmological isotropy of the large-scale structure of the Universe has been tested with the largest all-sky catalogue of GCs present in the literature, PSZ2-Union, released by the Planck Collaboration (Ade et al. 2015b,c). More specifically, we mapped the angular distribution of GCs through the celestial sphere using a geometrical and statistical test, named sigma-map analysis, which only depends on the coordinates where the cosmic objects are located (in other words, this means that it does not depend on any cosmological model assumption) in the sky if the assumption of large-scale isotropy is actually valid. Accordingly, any departure from statistical isotropy of the data would be revealed by departures of the sigma-map power spectrum when compared with the mean simulated spectra. Since we have probed large angular scales,

$1 \leq \ell \leq 10$, such discrepancy would suggest a possible failure of the CP as a valid assumption to describe the cosmic web.

The sigma-map analysis show that there is no statistically significance indication for anomalous clustering in the PSZ2-Union catalogue, and hence we report no suggestion for violation of statistical isotropy that might be, for instance, possible linked with the CMB features, or large-scale velocity flows, that we previously discussed. As a matter of fact, the sigma-map multipole decomposition, via S_ℓ 's, shows that there is good agreement between the real data and the MC realisations in large angular scales ($> 18^\circ$) once its hemispherical variance can be explained only in terms of the incomplete sky coverage, and the sky exposure, of the data.

Finally, our main conclusion is that the large-scale structure is in a good agreement with the fundamental assumption of cosmic isotropy in large angular scales. Nevertheless, we emphasize that it is crucial to repeat and provide new tests of such fundamental hypothesis with current data, and specially with future catalogues. For instance, eROSITA (Merloni et al. 2012) is expected to provide an all-sky sample of $n_{GCs} \sim 10^5$, thus, it may enormously enhance the precision of the test carried out in this work. Furthermore, the prospect of much larger data sets of different cosmic objects, e.g., galaxies, radio sources, or supernovae, that future missions such as Euclid (Amendola et al. 2013), LSST (Abell et al. 2009) and SKA (Maartens et al. 2015; Schwarz et al. 2015b) are expected to deliver, would enable us to test not only the isotropy, but the homogeneity assumption as well, with unprecedented precision.

ACKNOWLEDGMENTS

We thank Mariachiara Rossetti for useful discussions about the PSZ2 catalogue. CAPB Jr. acknowledges CAPES for the financial support. AB and ISF acknowledge the *Science without Borders Program* of CAPES and CNPq, for a PVE project (88881.064966/2014-01) and a PDE fellowship (234529/2014-08), respectively. JSA acknowledges financial support from CNPq, FAPERJ and INEspaço. We also acknowledge the HEALPix package, as many results obtained in this work have been derived using this software. This research has made use of the NASA / IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The Planck Sunyaev-Zeldovich catalogue used here is based on observations obtained with Planck (<http://www.esa.int/Planck>), an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada.

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